Introduction to Time & Frequency

Yann Le Coq
FIRST-TF
(CNRS/ENSMM/LNE/OCA/OP-PSL/SU/UCA/UFC/USPN/UTBM)

Outline

1) What is time ?

2) How to measure it ?

3) How to characterize such measurement :
Noise, Instability and Accuracy

4) How to make a common time reference and dispatch it ?

5) Risks/cybersecurity

Outline

1) What is time ?

2) How to measure it ?

3) How to characterize such measurement :
Noise, Instability and Accuracy

4) How to make a common time reference and dispatch it ?

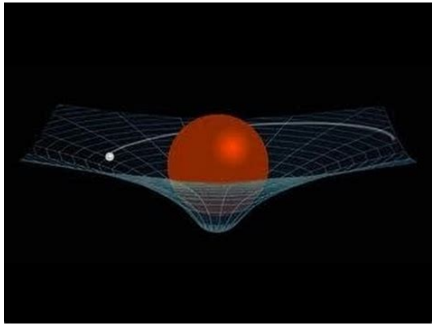
5) Risks/cybersecurity

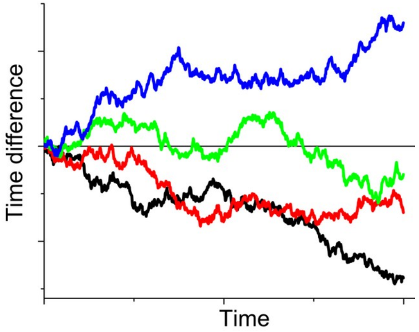
What is time ?

"What, then, is time?
If no one asks me, I know;
if I wish to explain to him who asks, I know not"
St Augustine (Confessions XI, ~400AD)

Common sense = Newtonian time = universal coordinate of events
(Note : different from Aristotle & Leibnitz point of view → maybe not so "natural")

Modern Physics: not so simple ! (relativity, quantum mechanics, etc…)
→ only "proper time" is truly meaningful ; "universality" requires some ~arbitrary collective decisions





Outline

1) What is time ?

2) How to measure it ?

3) How to characterize such measurement :
Noise, Instability and Accuracy

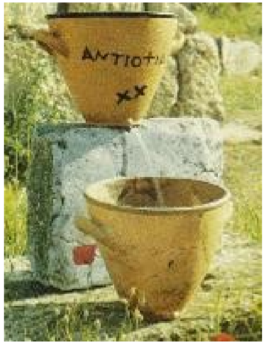
4) How to make a common time reference and dispatch it ?

5) Risks/cybersecurity

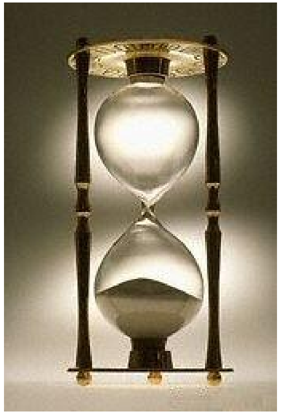
How to measure (proper) time

Needs something that changes in a regular and predictable/reproducible manner

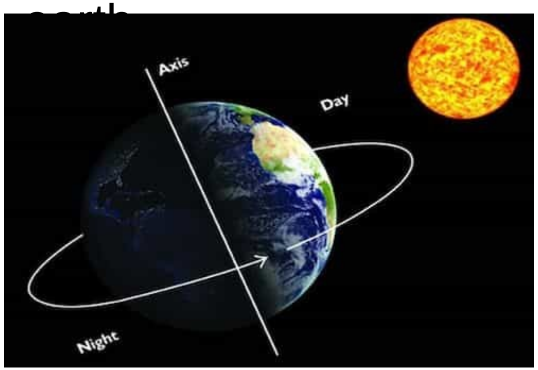
Water clock



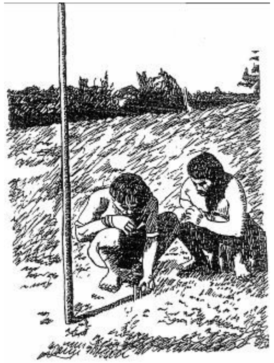
Hour glass

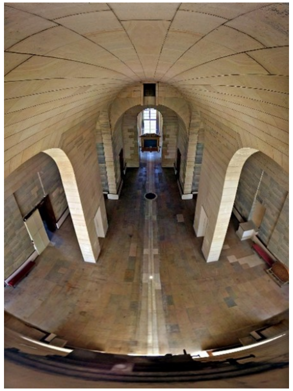


A “universal” good candidate: rotation of the earth



$$t = K \times \theta_{\mathrm{earth}}$$



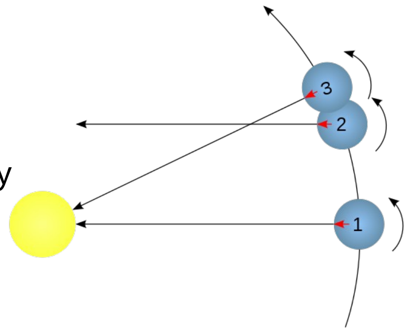


Gnomons, sundials, meridian telescopes

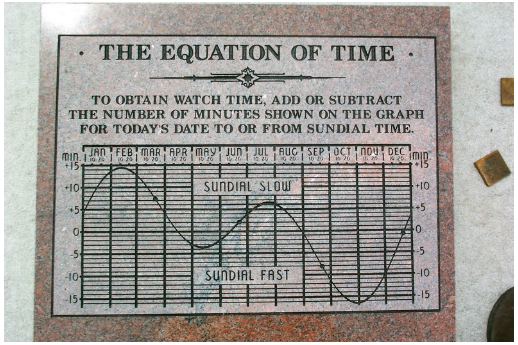
Rotation of the earth as timekeeping

Until 1956, SI unit of time (s) defined as : 1/86400 of the mean solar day

solar/sidereal day



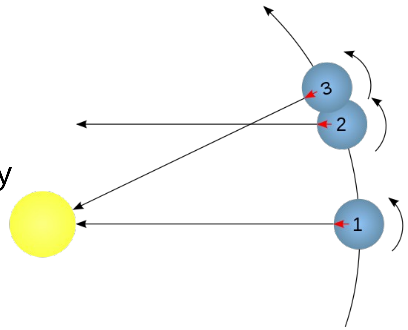
Equation of time



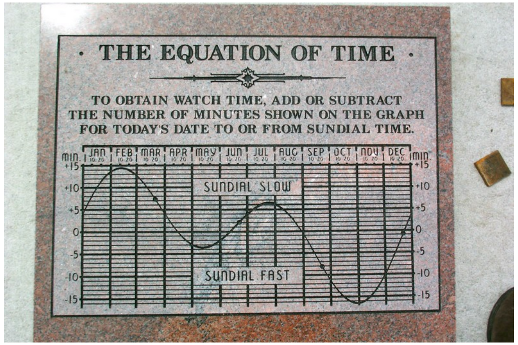
Rotation of the earth as timekeeping

Until 1956, SI unit of time (s) defined as : 1/86400 of the mean solar day

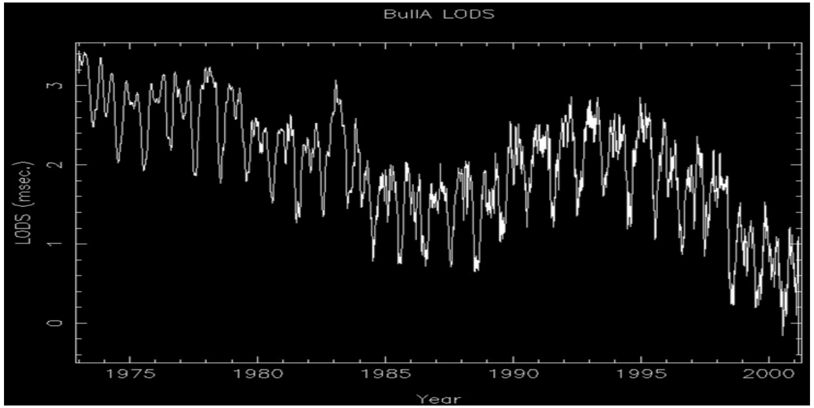
solar/sidereal day



Equation of time



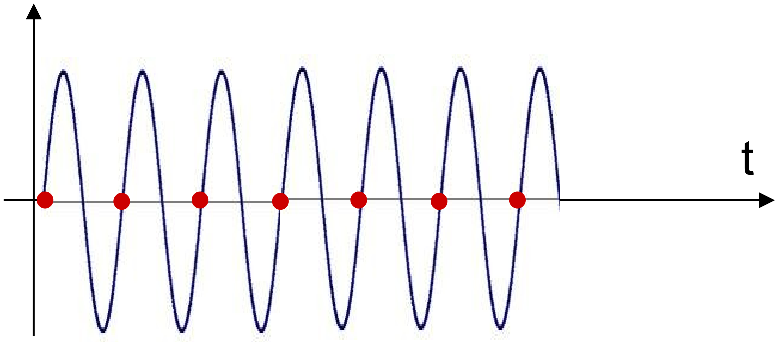
But it seriously fluctuates !
- tides (moon, sun)
- inner effects (core-mantle interface)
- atmosphere/meteorology effects
- hydrology
- seismic effects (earthquakes, tsunnamis)
-...



1956 to 1967 : the fraction 1/31,556,925.9747 of the tropical year 1900
1 tropical year = 365,2422 solar days = 366,2422 sidereal days

Man-made oscillators/frequency standards

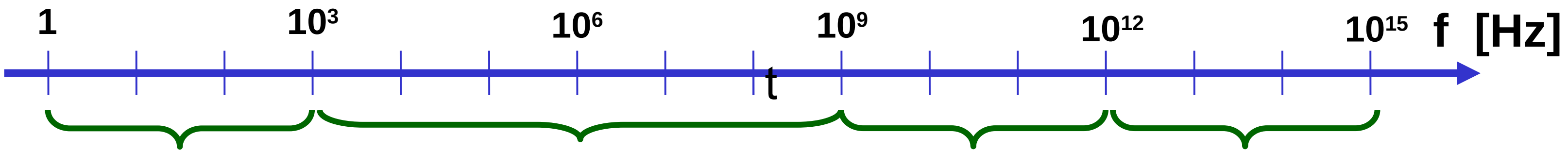
Physical signal



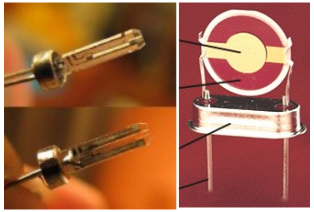
$$s(t) = A\cos(2\pi\nu_0 t) = A\cos\left[\Phi(t)\right]$$

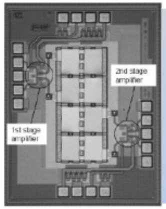
$$t = \frac{\Phi}{2\pi\nu_0}$$

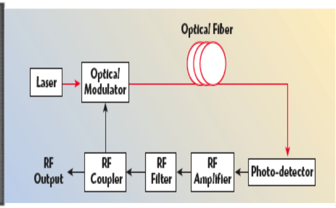
(generally update tmeasured in a discrete manner – typically each time $\phi = 2n\pi$)

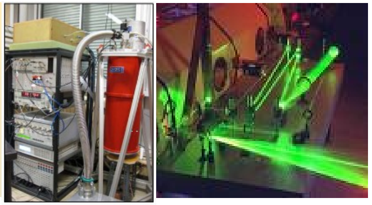


Oscillator → mechanical | quartz (+ MEMS) | microwave | laser









+ atomic transition between energy levels reference

Outline

1) What is time ?

2) How to measure it ?

3) How to characterize such measurement :
Noise, Instability and Accuracy

4) How to make a common time reference and dispatch it ?

5) Risks/cybersecurity

The noisy oscillator

Real Oscillator :
$$\begin{cases} s(t) = A_0[1+\alpha(t)]\cos[2\pi\nu(1+y(t))t+\phi_0] \\ s(t) = A_0[1+\alpha(t)]\cos[2\pi\nu t+\phi(t)+\phi_0] \\ s(t) = A_0[1+\alpha(t)]\cos[2\pi\nu(t+x(t))+\phi_0] \end{cases}$$

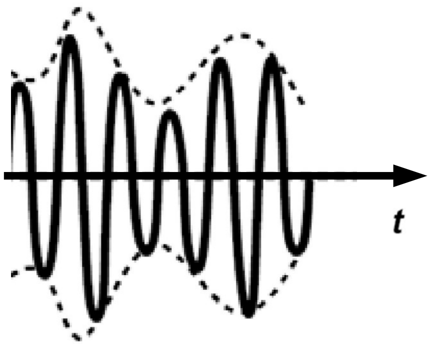
Different descriptions of the same signal...

$\alpha(t)$: amplitude noise

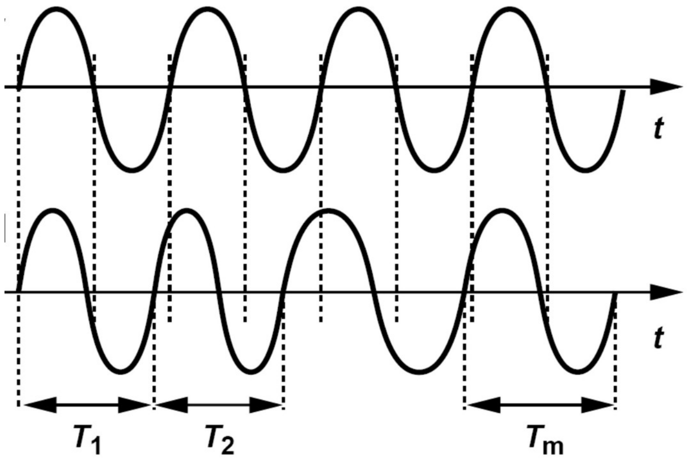
Different descriptions of the same effect...

- $y(t)$: relative frequency noise
- $\phi(t)$: phase noise
- $x(t)$: timing noise

amplitude noise



frequency/phase/timing noise

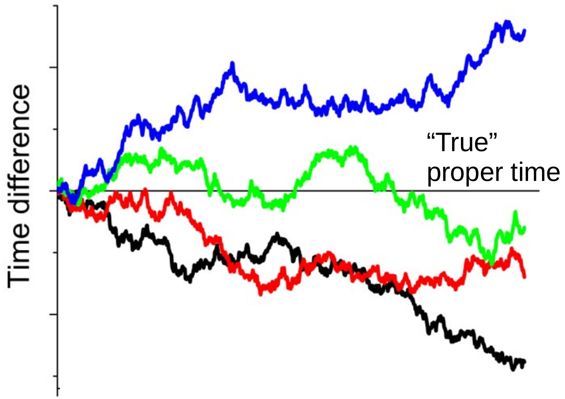


Time measurement, Noise and Divergence

Real Oscillator :

$$s(t) = A_0[1+\alpha(t)]\cos[2\pi\nu(1+y(t))t+\phi_0]$$
$$s(t) = A_0[1+\alpha(t)]\cos[2\pi\nu t+\delta\phi(t)+\phi_0]$$
$$s(t) = A_0[1+\alpha(t)]\cos[2\pi\nu(t+x(t))+\phi_0]$$

Different descriptions of the same signal...



$\alpha(t)$: amplitude noise (physically bounded)

Different descriptions of the same effect...

$y(t)$: relative frequency noise (physically bounded)

$\phi(t)$: phase noise (**not physically bounded**, always divergent !)

$x(t)$: timing noise (**not physically bounded**, always divergent !)

Two **real** (un-coupled) clocks, as **identical** as can be, measuring **the same proper time** will **always diverge** after a while unless you apply some feed-back/coupling mechanism

Mathematical tools for random signals

Real Oscillator :
$$\begin{cases} s(t) = A_0[1+\alpha(t)]\cos[2\pi\nu(1+y(t))t+\phi_0] \\ s(t) = A_0[1+\alpha(t)]\cos[2\pi\nu t+\phi(t)+\phi_0] \\ s(t) = A_0[1+\alpha(t)]\cos[2\pi\nu(t+x(t))+\phi_0] \end{cases}$$

Different descriptions of the same signal...

Most utilized statistical tools in TF, for a random variable v (unit [u]):
- **power spectral density** $S_v(f)$ (unit u²/Hz, often dB(u²/Hz)), sometimes $\sqrt{S_v(f)}$ (unit u/√Hz)

$S_\alpha(f)$ $S_y(f)$ $S_\phi(f)$ $S_x(f)$ *etc.*

➡ ~ rms fluctuations measured in a BW of 1Hz around a Fourier frequency f (mostly used for "short" <1s timescales)

- **2-sample variances/deviations (ADEV, TDEV,...)**:

Un-normalized ADEV (can use it also for random variables other than frequency…)

$\sigma_y(\tau)$ $\sigma_{\nu y}(\tau)$[Hz] $\sigma_x(\tau)$[s]

ADEV of y

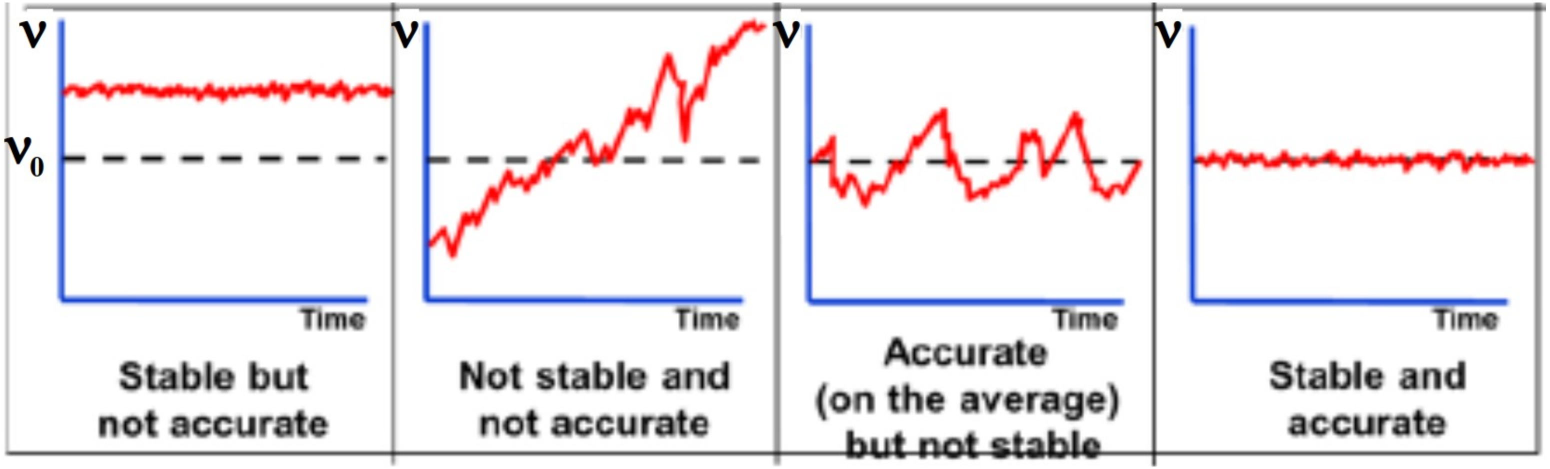
➡ ~ "typical" fluctuations between consecutive measurements of duration τ (mostly used for "long" >1s timescales)

Instability and accuracy

Real frequency standard at ν_0: $s(t) = A_0[1+\alpha(t)]\cos[2\pi\nu_0(1+\epsilon+y(t))t+\phi_0]$

Instability: quantifies the frequency fluctuations at a given time scale τ
mathematical tools: 2-sample variance (AVAR) and family, extracted from $y(t)$
decreases (more or less) with increasing τ

Systematic error/bias ϵ: how wrong you believe you can be from the target frequency
You can only estimate it (and maybe you forgot something important)!
(note: low instability often helps such estimation experimentally)



(From J. Vig tutorial)

Instability and accuracy

Real frequency standard at ν_0: $s(t) = A_0[1+\alpha(t)]\cos[2\pi\nu_0(1+\epsilon+y(t))t+\phi_0]$

Instability: quantifies the frequency fluctuations at a given time scale τ
mathematical tools: 2-sample variance (AVAR) and family, extracted from $y(t)$
decreases (more or less) with increasing τ

Systematic error/bias ϵ: how wrong you believe you can be from the target frequency
You can only estimate it (and maybe you forgot something important)!
(note: low instability often helps such estimation experimentally)

Note : “precision” is rarely used appropriately, and most people only have a vague understanding of what it means ⇨ mostly stay away from it !

Outline

1) What is time ?

2) How to measure it ?

3) How to characterize such measurement :
Noise, Instability and Accuracy

4) How to make a common time reference and dispatch it ?

5) Risks/cybersecurity

Problems of clocks and timekeeping

1) Clocks only measure their proper time, not an "absolute" time (which doesn't exist…)

➡ comparing (good) clocks require compensation of relativistic effects (gravitational shift, relative speed)… level of knowledge of the correction ?

2) Multiple clocks – even when measuring the same proper time – will always diverge (in an unpredictable way)

➡ Every clock in the world needs some kind of feed-back to stay (more or less) in agreement with the others (how often = "holdover")

Solution:
- clocks comparisons
- International collaboration (BIPM) and timescale steering (EAL, TAI, UTC(k), UTC)

Frequency and Time dissemination

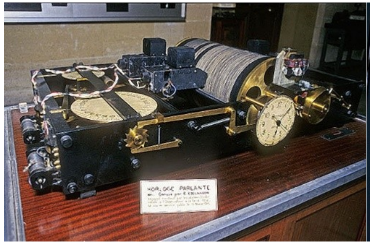
Local clock/ frequency standard → Propagation time t_d → Remote user

t_d constant: desynchronisation

t_d fluctuates: desynchronisation + desyntonisation (frequency detuning)

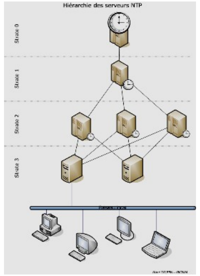
a priori knowledge of t_d allows (up to a point) correction

Talking clock

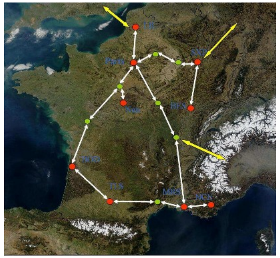



Longwave transmission (DCF77, ALS162, ...)

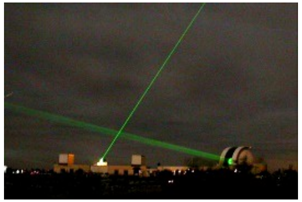

Telecom (NTP, WR)



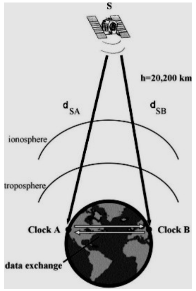
Fiber



Laser links



GNSS
TWSTFT



Frequency and Time dissemination

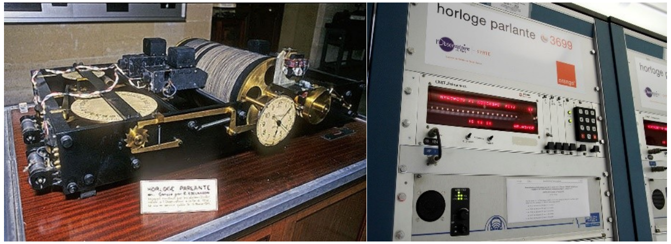
Local clock/ frequency standard

Propagation time t_d

Remote user

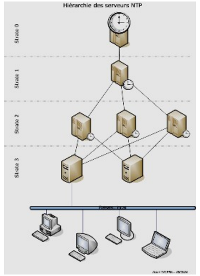
Two-way transfer: allows measuring t_d, and correcting for it

Talking clock

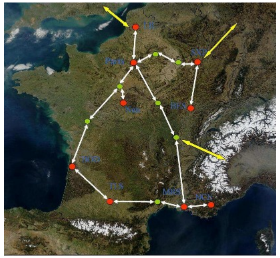


Longwave transmission (DCF77, ALS162, ...)

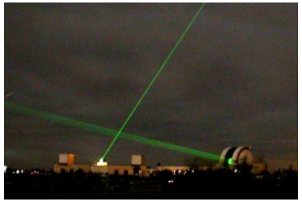
Telecom (NTP, WR)



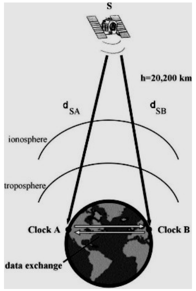
Fiber



Laser links



GNSS TWSTFT



Outline

1) What is time ?

2) How to measure it ?

3) How to characterize such measurement :
Noise, Instability and Accuracy

4) How to make a common time reference and dispatch it ?

5) Risks/cybersecurity

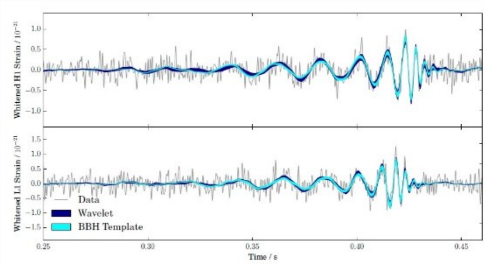
Time references and distribution networks are everywhere...

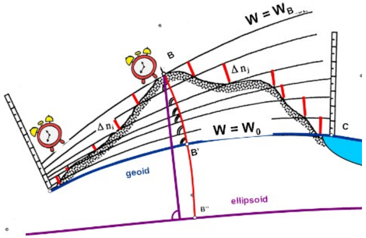
- Fundamental metrology (SI units),
- Fundamental physics (drift of fundamental constants, gravitational shift, …)
- Detection of gravitation waves, relativistic chronometric geodesy
- Astronomy (pulsars time tagging)

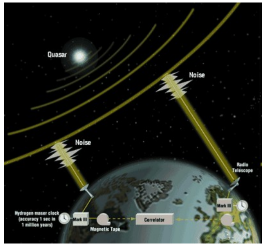
- Local oscillators in any electronic devices, PLL, filters, sensors
- Ranging, positioning, navigation, GNSS
- Network synchronisation: telecom, datacenter, smart grids, DSN, VLBI, SKA
- RADAR, LIDAR, atmosphere analysis, …

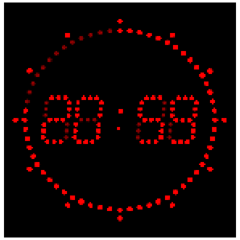
- Banks (MIFID 2), justice, police, hospitals, etc. → requirements for traceability

...



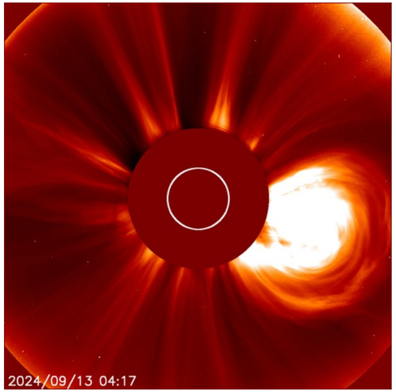


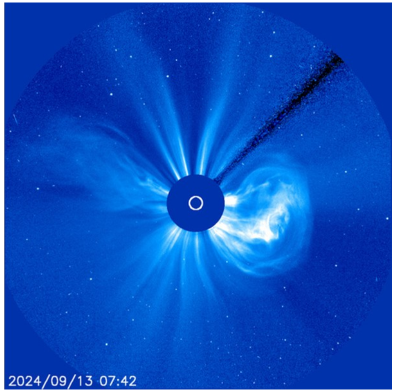


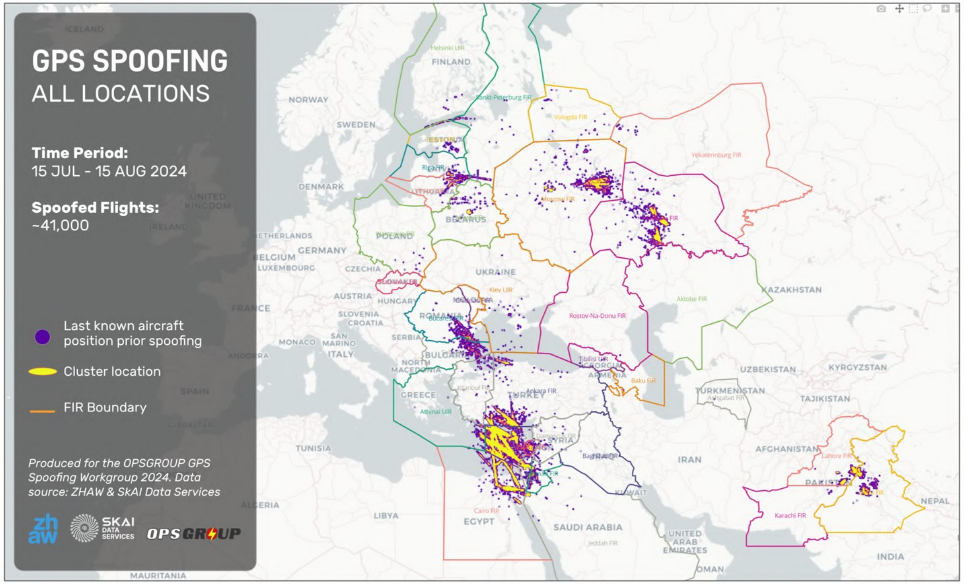


Risks associated with GNSS (and others...)

- GNSS degradation
  - European/ worldwide problem
    - Ionosphere perturbation
    - Constellation(s) problems
  - RF interference (jamming/ spoofing)
    - Long range (~100km)
    - Local (~1-10km)
  - Receiver problem
    - Individual/ specific







Cyber-security objectives

Availability	Integrity/ authenticity	Traceability	Confidentiality
jamming	spoofing	lawsuit	military